EXPERIMENTAL AND ANALYTICAL INVESTIGATIONS ON THERMAL PERFORMANCE OF SLIM FLOOR BEAMS WITH WEB OPENINGS IN FIRE

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EXPERIMENTAL AND ANALYTICAL INVESTIGATIONS ON THERMAL PERFORMANCE OF SLIM FLOOR BEAMS WITH WEB OPENINGS IN FIRE

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ABSTRACT

Steel beams with web openings are widely used in constructions to reduce the weight of steelwork, especially in structures comprising of traditional composite beams with down-stand steel sections. In recent times, the use of steel sections with web openings has become common as slim floor beams since they offer a reduction in weight of the steelwork, accommodate services within the floor depth and provide the plug composite action. Though these web openings offer several benefits in slim floor beams, however, they induce the material discontinuity in the web affecting their shear capacity and thermal behaviour. During the pouring of concrete, the steel in the web openings is replaced by the concrete with a low thermal conductivity. This research presents findings from experimental and analytical investigations conducted to study the thermal behaviour of slim floor beams with web openings in fire. For this purpose, an experimental investigation was conducted to study the thermal response of slim floor beams in fire. Data obtained from the fire test shows that the presence of web openings has a significant influence on temperature development across the steel section as well as along the span of these beams. The temperatures on the web below the openings are higher in comparison to those on the adjacent web-posts. It is also observed that temperatures on the web above the openings are significantly lesser than those on the adjacent web-posts. Parametric studies conducted using the finite element modelling show that smaller opening spacings and larger opening sizes have a severe influence on the thermal behaviour of these beams in fire. The findings of this research will help in selecting appropriate opening sizes and spacings in slim floor beams to avoid any severe temperature distributions in fire and to ensure their suitable utility.

Keywords: Slim floor beams, web openings, thermal response, fire tests, finite element modelling.

1 INTRODUCTION

Though the use of composite beams offers longer floor spans, however, the depth of these beams being higher in comparison to the reinforced concrete beams, is a major disadvantage especially in tall buildings. On the other hand, the use of slim floor beams in high-rise buildings is advantageous due to their shallower depth resulting from their partial encasement within the floor [1]. This partial

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encasement also improves their fire resistance and their stiffness. The increase in stiffness enhances the bending resistance of these beams by reducing deflections and vibrations in service conditions. Use of the slim floor beams aids in reducing the construction cost as they consume lesser building materials. The combination of these beams with the metal decking reduces the construction time and eliminates any requirements of formwork and scaffolding [2] [3]. Slim floor beams also help in assimilating the services within the floor depth through the web openings. Though the web openings offer numerous advantages, however, they also reduce the shear resistance of these beams. Previous experimental and analytical investigations have shown that the concrete between the flanges of the steel section in these beams contributes towards their shear capacity compensating for the loss of the steel web. In some cases, this concrete increases their shear capacity significantly, twice as compared to that offered by the bare steel beam [4] [5]. Further, experimental investigations are also conducted to study the longitudinal shear resistance offered by these beams in terms of the plug composite action. These investigations have shown that the plug composite action improves the longitudinal shear transfer mechanism in these beams [6].

1.1 Aims and objectives

The work presented herein is an experimental and analytical investigation conducted to study the effect of web openings on the thermal response of slim floor beams in fire. This investigation addresses the effect of material discontinuities and resulting influences on the thermal behaviour of slim floor beams in fire. The data acquired from this test is one of its kind and will help to understand the behaviour of these beams at elevated temperatures. Analytical investigations on the spacings and sizes of web openings will highlight the influence of these parameters on the thermal behaviour of these beams in fire.

1.2 The scope of research

The scope of this study is limited to thermal behaviour only and no investigations are conducted to analyse the influence of the web openings on the structural response of slim floor beams in fire.

2 EXPERIMENTAL PROGRAMME

2.1 Test specimen and heating conditions

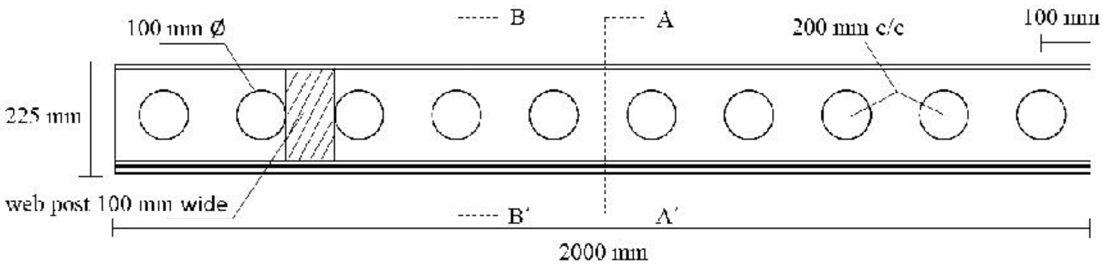
A fire test was conducted on a slim floor beam assembly to analyse any influence of the presence of web openings on their thermal behaviour in fire. As mentioned before, the scope of this study is limited to investigations on thermal behaviour only, hence, no external loads are applied during the test. The tested slim floor beam assembly is 1000 mm wide and 2000 mm long, corresponding to the size of the furnace which is 2000 mm x 2000 mm in the plan. The slim floor beam consisted of a steel section, HEA-220 and a steel plate 400 mm wide and 15 mm thick made from grade S355 steel and welded to the bottom flange along its length. The overall depth of the steel section is 225 mm including the welded plate, *Fig 1(c)*. The composite floor consisted of a steel decking and normal weight concrete with a target strength of 30 MPa at 28 days. The steel decking used for the floor construction is MD 50, a high performance, profiled, galvanised steel floor decking used for the construction of composite floor slabs. Total depth of the test assembly is 280 mm including a 55 mm layer of concrete above the top flange and the 15 mm thick welded steel plate, *Fig 1*. Concrete above the top flange is reinforced using A-142 steel mesh with flying ends and with minimum laps of 400 mm. This reinforcing mesh is placed using 15 mm deep spacers to maintain its position above the top flange. The sides of the slim floor beam assembly are designed using steel sheets which serve as a permanent formwork during concreting, *Fig 1(b)*.
The steel section of the slim floor beam is fabricated with 100 mm diameter web openings spaced at 200 mm centres throughout its length as shown in *Fig 1(a)*. In total, 10 openings are fabricated in the web in such a way that their centres coincide with the centreline of the web, 94 mm from the top and the bottom flange. In between these web openings, a solid web with a minimum width of 100 mm is produced. This solid web is referred to as the web-post in this paper. The first openings at

both ends of the steel section are centred at 100 mm from the edges. The depth of the solid web above and below the edge of openings is 44 mm.

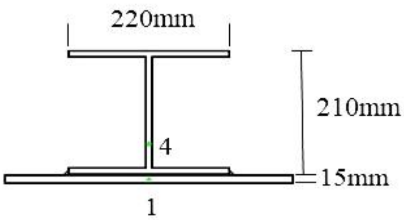
Keeping in view the scope of this research, only thermal data is recorded while no arrangements are made to record any deformations during the test. Temperatures within the furnace and on the slim floor beam assembly are acquired using K-type thermocouples. The furnace temperatures are monitored via five thermocouples to ensure the heating conditions are in accordance with the standard fire, while the temperatures on the slim floor beam assembly are monitored through thermocouples positioned on the steel beam at two locations, section AA′ and section BB′. The temperatures at section AA′ are monitored using two thermocouples, one on the middle of the welded steel plate and the other on the web-post at 40 mm from the inner edge of the bottom flange, *Fig 1(d)*. On the other hand, temperatures at the opening are monitored at section BB′ using three thermocouples. Two of these thermocouples are positioned in the middle of flanges, one each on the top and the bottom flange, while the third thermocouple is positioned on the web at 40 mm from the inner edge of the bottom flange, adjacent to the thermocouple on the web-post at section AA′, *Fig 1(e)*. Thermocouples 3 and 4 are at same distances from the bottom flange *Fig 1(d) & Fig 1(e).*

(a) Steel beam with web openings

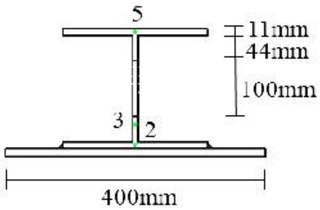
(b) Test assembly



(c) Elevation of the beam



(d) Section at AA′

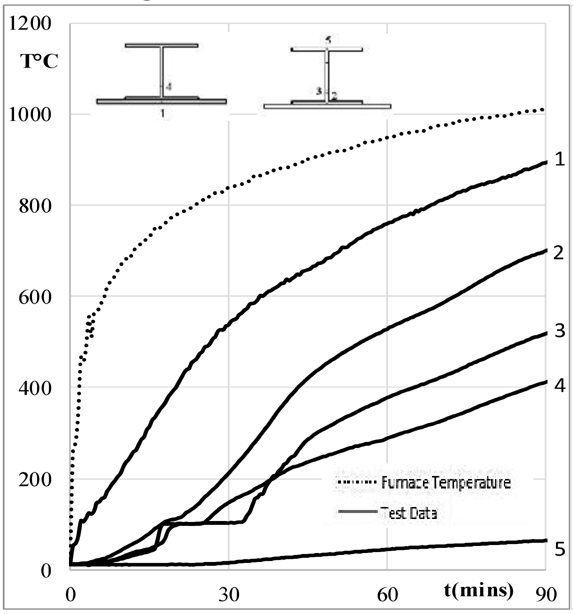


(e) Section at BB′

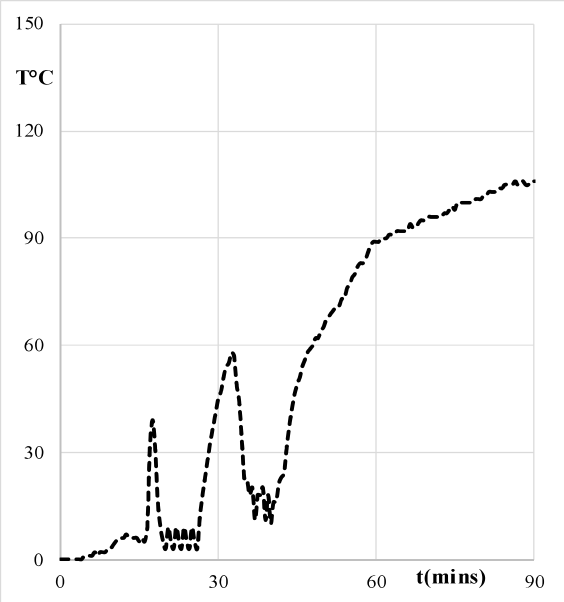
Fig 1: Details of the test assembly

2.2 Test procedure and results

The fire test on the slim floor beam assembly with web openings was conducted at Fire Safety Engineering Research and Technology (FireSERT), Ulster University on the 18th of January 2018. The test conducted using a gas-fired furnace lasted for 90 minutes during which thermal data was recorded for the furnace and for the slim floor beam. The test assembly was placed on top of the furnace while the remaining part of the furnace top was covered using concrete slabs. The interface between the test assembly and the concrete slabs as well as any openings were filled using ceramic fibre blanket to control the heat and smoke and to allow any deformations resulting at higher temperatures. Hence, the ceramic fibre blanket not only served as an insulator but also served as a flexible filler to accommodate the beam deflections. The beam assembly was put on top of the furnace walls directly and no special support conditions were provided. To accommodate any expansion resulting at higher temperatures, no restraints were applied to the ends of the test assembly. All the thermocouples were connected to the data logging system where the temperatures were recorded for the whole duration of the test. Once the beam assembly was ready for testing, it was heated in accordance with the standard fire curve, ISO-834 [7] for a period of 90 mins after which the heating was discontinued.



(a) Recorded temperatures



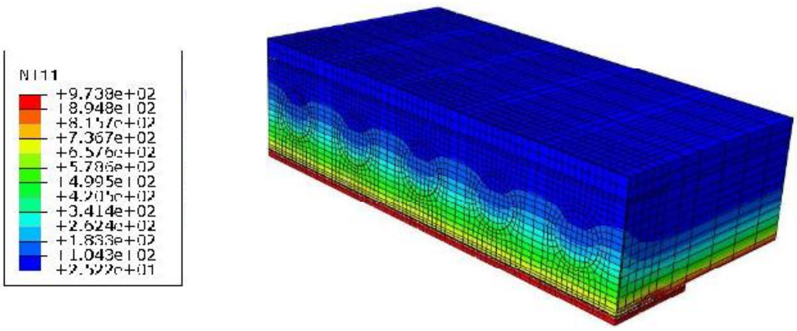
(b) The temperature difference between thermocouple 3 and 4

Fig 2: Recorded test data for the slim floor beam assembly with web openings

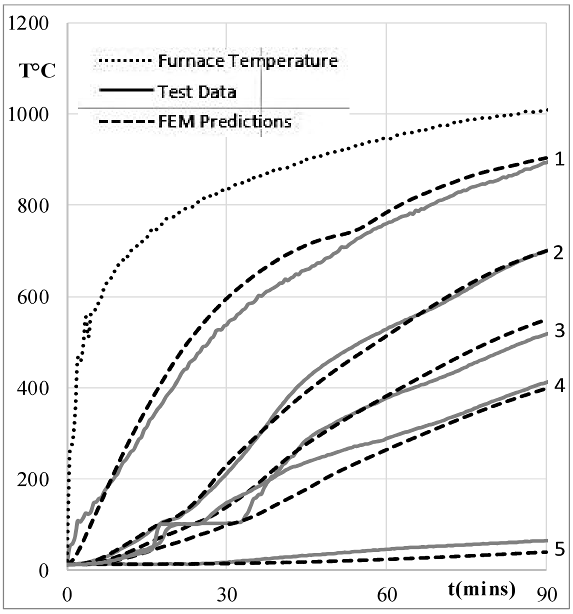
Data acquired during the fire test is in terms of the temperatures is presented in *Fig 2*. The numbers corresponding to temperatures in *Fig 2(a)* represent the thermocouple positions shown earlier in *Fig 1(d) and Fig 1(e)*. Alike other slim floor beams, there is a high thermal gradient across the section with the exposed lower parts being at higher temperatures in comparison to the unexposed upper parts. It is also seen that there is a significant temperature difference between thermocouples 3 and 4 positioned at the same distance from the inner edge of the bottom flange. Temperatures recorded on the web below the opening, thermocouple 3, are higher compared to those recorded at the adjacent location on the web-post, thermocouple 4. This temperature difference is presented in *Fig 2 (b)*, which shows a temperature difference of 90°C and 107°C after a fire exposure of 60 mins and 90 mins respectively. The resulting temperature difference is due to discontinuity of the steel in the web. The steel in the web opening is replaced by the concrete with as a low thermal conductivity which restricts the efficient flow of heat across the steel section. As a result, temperatures on the web under the opening are comparatively higher as compared to those on the adjacent web-post. The recorded test data suggests that the web openings in slim floor beams have a considerable influence on their thermal behaviour in fire conditions.

3 FINITE ELEMENT MODELING

Finite element modelling (FEM) for the test assembly is conducted using ABAQUS [8]. Though several studies have been conducted to analyse the behaviour of shallow floor systems in fire, these previous studies address the slim floor beams with no web openings [9] [10]. During the current study, FEM is first conducted for the validation of the fire test. During the validation process, a quarter of the test assembly is modelled and heated using the recorded furnace temperatures. All the boundary conditions are kept alike the test. Non-linear material properties, including the thermal conductivity, specific heat, and the density are taken from the codes [11] while 8-node hexahedral solid linear heat transfer elements (DC3D8) are used to model both steel and concrete. Heat transfer through the surfaces of the test assembly is modelled via convection and radiation. The convection coefficients for exposed and unexposed surfaces are taken as 25W/m^{2}K and 9W/m^{2}K respectively following the code recommendations [12]. Any heat transfer through radiation from the unexposed surfaces is ignored while the same for the exposed surfaces and for the cavity between the welded plate and bottom flange, is modelled using an emissivity of 0.7 following the recommendation of codes, [13] [14]. Perfect thermal contact is modelled between the steel and the concrete allowing efficient and full heat transfer following the methods presented in similar studies conducted previously on other types of shallow floor systems [9] [10].



(a) Thermal contours, FEM



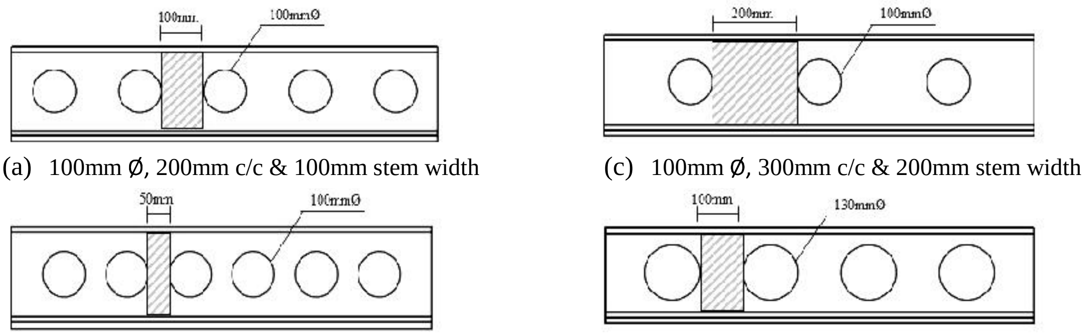
(b) Test vs FEM, the thermal predictions

Fig 3: FEM results and the model verification

The results obtained from FEM are presented in *Fig 3*. The thermal contours in *Fig 3(a)* show the influence of web openings on the heat transfer across the section and along the span of the slim floor beam. Alike the test, temperatures on the web below the opening are higher as compared to those predicted for the adjacent locations on the web-post. It can also be seen that the temperatures on the web above the opening are lesser than those predicted on the adjacent web-post at the same levels. The predicted temperatures from the FEM are plotted against the recorded test data in *Fig 3(b)* and are in good agreement for all thermocouple locations. Hence, the FEM method used in this study can predict the thermal response of slim floor beams having web openings with good accuracy and can be used to conduct sensitivity studies.

4 SENSITIVITY ANALYSIS

A sensitivity analysis was conducted to analyse the influence of the spacing and the size of the web openings on thermal behaviour of slim floor beams in fire. During this part of the research, the verified FEM method, discussed in section 3, was used. Different spacings of the web openings result in variable web-post widths as shown in *Fig 4*. Three investigations were conducted to analyse the effect of spacings of web openings. During these investigations, the size of the openings was kept 100 mm in diameter while the opening spacings were 200 mm, 150 mm and 300 mm. The minimum width of the web-post resulting from the variable opening spacings was 100 mm, 50 mm and 200 mm respectively, *Fig 4*. To investigate the effect of the opening size, FEM was conducted on a slim floor beam assembly having web openings of 130 mm diameter (equivalent to 70% of web depth) at 230 mm centres. Such an arrangement of the web openings results in a stem width of 100 mm, *Fig 4(d)*. The stem width for case (a) and (d) in *Fig 4* is same while the size of the opening in both cases is different. The dimensions of the slim floor beam assembly used during the sensitivity analysis are same as the one used during the model verification discussed in section 3.



(a) 100mm Ø, 200mm c/c & 100mm stem width

(c) 100mm Ø, 300mm c/c & 200mm stem width

(b) 100mm Ø, 150mm c/c & 50mm stem width

(d) 130mm Ø, 230mm c/c & 100mm stem width

Fig 4: Sensitivity study, the effect of the spacing and size of openings

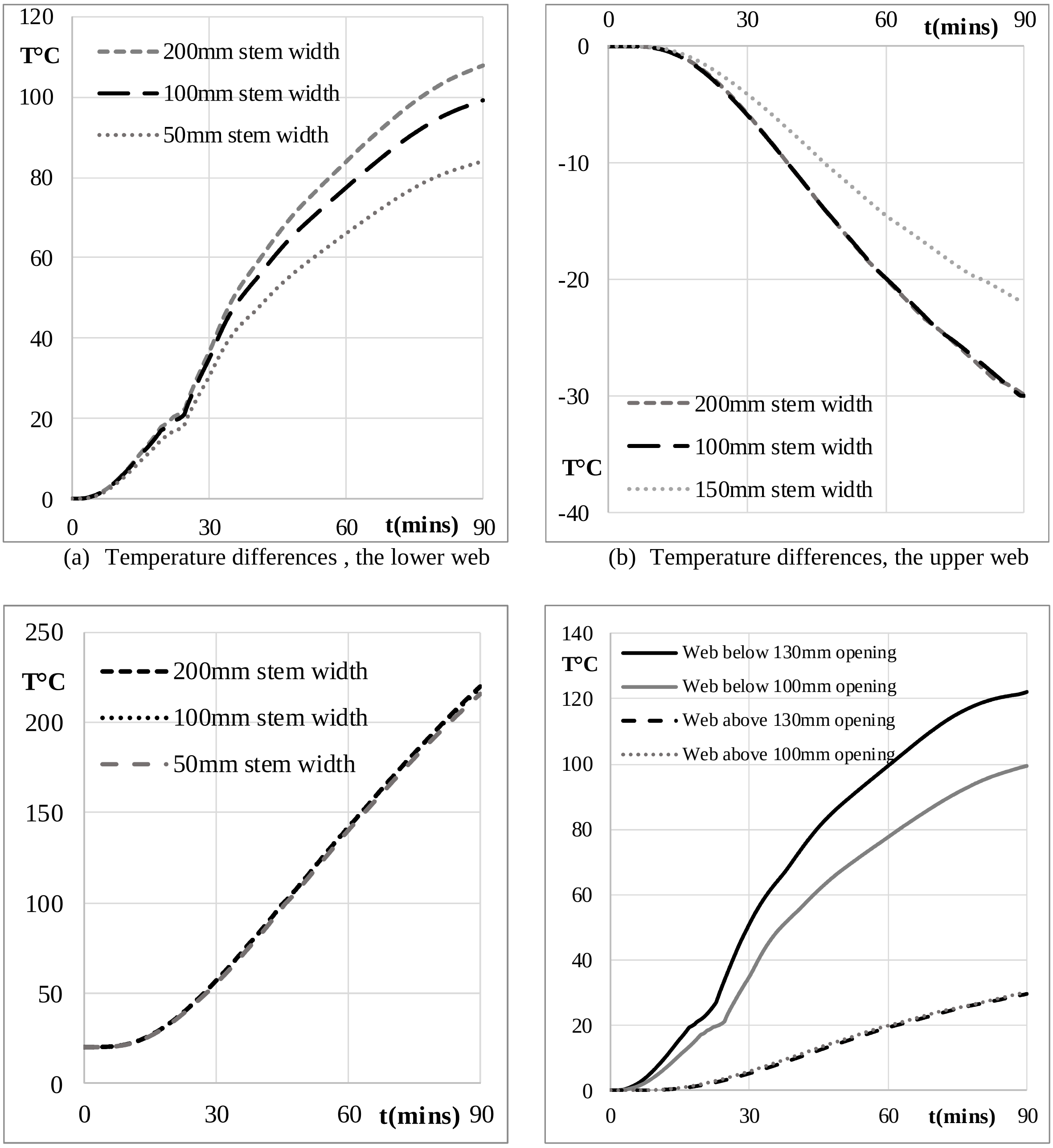
4.1 Effect of the spacing or the stem width

Results obtained from FEM on the effect of opening spacings are presented in *Fig 5(a), (b) & (c)*. It is seen in *Fig 5(a)* that the temperature differences between the parts of web below the opening and the adjacent web-posts are lesser for smaller opening spacings as compared to those predicted for larger spacings. This means that for smaller web-post widths and closely spaced openings, temperatures on the web under the opening as well as on the web-post are higher in comparison to those for slim floor beams with larger web-post widths. Hence, smaller opening spacings produce more severe temperatures in slim floor beams. The temperatures differences on the upper parts of the web are less severe as compared to those for the lower parts. Temperatures predicted for the web above the opening are lesser than those predicted for the adjacent web-post, *Fig 5(b)*. These temperature differences are higher for smaller web-post widths as compared to larger widths, *Fig 5(b)*. It is interesting to note that the predicted temperatures in the middle of the stem for all cases with same opening sizes are same irrespective of their spacings, *Fig 5 (c)*.

4.2 Effect of the web opening size

The results from FEM show that the increase in the size of the opening also influences the thermal behaviour of slim floor beams. This increase in the size of openings induces higher temperature difference between parts of the web under the opening and on the adjacent web-post, *Fig 5(d)*. The effect of the opening size is less significant for parts of the web above the opening, *Fig 5 (d)*.

These results show that the spacing of the openings and their size has an influence on the thermal response of slim floor beams with web openings in fire. Closely spaced openings and their larger sizes have more severe effects on the thermal behaviour of slim floor beams in fire.



(a) Temperature differences , the lower web

(b) Temperature differences, the upper web

(c) Predicted temperatures in the middle of the stem for various opening spacings

(d) Effect of the opening size

Fig 5: Influence of the opening spacings and sizes on thermal behaviour of slim floor beams

5 CONCLUSIONS

This research presents the findings of an experimental and an analytical investigation conducted to study the influence of the web openings on thermal behaviour of slim floor beams in fire. During the experimental investigation, it was found that the presence of web openings has a considerable influence on their thermal behaviour in fire. It was observed that the presence of the web openings results in higher temperatures on the parts of web below the openings as compared to those on the adjacent web-post. During the sensitivity study, it was observed that the smaller spacing of openings results in more severe temperature distributions, producing higher temperatures on the web below the opening as well as on the web-post. Temperatures on the centre of the web-post were found to be unaffected by the variations in spacing of the openings. Investigations on the influence of the opening sizes show that the temperature differences on the bottom part of the steel web, under the opening and on the adjacent web-post, are more severe for larger opening sizes as compared to those for smaller openings. Hence, smaller spacing of openings and larger opening sizes have a severe influence on the thermal behaviour of slim floor beams in fire.

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